Charmonium Review

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During the last few years there has been a renaissance in charm and charmonium spectroscopy with higher precision measurements at the $\psi^{'}$ and $\psi(3770)$ coming from BESII and CLEOc and many new discoveries coming from B-factories. In this paper, I will review the status of $\psi(3770)$ and below.

1. Introduction

An admonishment says "May you live in exciting times". It turns out that for charm and charmonium spectroscopy, we are. Only 10 $C\bar{C}$ resonances were discovered from 1974 to 1977; none were discovered from 1978 to 2002. However from 2002 to 2005, seven new $C\bar{C}$ resonances were discovered by Belle, BaBar, CLEOc, CDF, and D0. I will review the $\psi(3770)$ and below, where there has been much progress from BES, CLEOc, B-factories, etc. Brian Petersen will cover the new states: X, Y, Z, etc.

2. Old but new states

2.1. $\eta_c^{'}$

Prior to 2002, there was an unconfirmed candidate for the $\eta_c^{'}$ by the Crystal Ball experiment [1] at a mass of 3594 ± 5 MeV/c^2. In 2002, Belle observed clear peaks in the X mass distribution in $B \to KX, X \to K_S K\pi$ at the η_C, the J/ψ, and at a mass of 3654 ± 10 MeV/c^2 [2]. CLEO [3] and BaBar [4] quickly confirmed the higher mass value in $\gamma\gamma \to K_S K\pi$ with mass measurements of 3642 MeV/c^2 and 3633 MeV/c^2, respectively. Belle also found a peak in $e^+e^- \to J/\psi X$ at $M_X = 3630$ MeV/c^2 [5]

Combining the results, excluding Crystal Ball, yields a mass of $M_{avg} = 3637 \pm 4$ MeV/c^2, and hyperfine splittings of $\Delta M(1S) = M_{J/\psi} - M_{\eta_c} = 117 \pm 1$ MeV/c^2 and $\Delta M(2S) = M_{\psi(2S)} - M_{\eta_c^{'}} = 49 \pm 4$ MeV/c^2. The higher mass is more consistent with lattice calculations (LQCD) and potential models [6].

2.2. h_c

The h_c or $^1P_1 C\bar{C}$ state has $J^{PC} = 1^{+-}$. This state is important to learn more about the hyperfine (spin-spin) interaction of P wave states. It is expected to have a mass near the center of gravity of the $^3P_1$ states $m_{h_c} = m_{c.of g.} = 3525.31 \pm 0.07$ MeV/c^2, to be narrow ($\Gamma < 1$ MeV/c^2), and to decay to $\eta_c\gamma$.

In 1992, E760 using 16 pb^{-1} of $p\bar{p}$ data observed a structure near 3526 MeV/c^2 in $p\bar{p} \to J/\psi\pi^0$ [7]. The successor experiment E835 using 113 pb^{-1} of data was unable to confirm this peak! However E835 also searched for $p\bar{p} \to h_C \to \gamma\eta_C, \eta_C \to \gamma\gamma$ and found a signal at $M = 3525.8 \pm 0.2 \pm 0.2$ MeV/c^2 for $\Gamma = 0.5$ to 1 MeV/c^2 [8].

CLEOc quickly substantiated this with evidence for h_C production from $e^+e^- \to \psi(2S) \to \pi^0 h_C \to 3\gamma\eta_C$ at CESR [9] with a sample of 3×10^6 $\psi(2S)$ events. Using an inclusive analysis where they measured the mass recoiling from the π^0, they obtained $M(h_C) = 3524.9 \pm 0.7 \pm 0.4$ MeV/c^2. From an exclusive analysis, where they measured h_C decays to $K_S K\pi$, $K_L K\pi$, $KK\pi\pi$, $\pi\pi\pi\pi$, $KK\pi^0$, and $\pi\pi\eta$, they obtained $M(h_C) = 3523.6 \pm 0.9 \pm 0.5$ MeV/c^2. The consistency between the two measurements was good giving an overall $M(h_C) = 3524.4 \pm 0.6 \pm 0.4$ MeV/c^2,

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and a product branching fraction $B(\psi(2S) \to \pi^0 h_C)B(h_C \to \gamma\eta_C) = (4.0 \pm 0.6 \pm 0.4) \times 10^{-4}$, in agreement with a PQCD prediction of $B = (1.9-5.8) \times 10^{-4}$ [10]. The mass splitting $\Delta M_{hf} = < M(^3P_J) > -M(^1P_1) = 1.0 \pm 0.6 \pm 0.4 \mathrm{MeV}/c^2$ agrees with expectations (≈0), but the sign and difference are not yet well enough determined to provide a real test.

Now the charmonium family below the $\psi(3770)$ is complete, and the mass values can be used in potential models to predict masses of higher states.

3. $\psi(2S)$ radiative and hadronic transitions

3.1. $\psi(2S)$ radiative transitions

CLEOc with its CsI calorimeter ($\Delta E/E = 5.0$ % at 100 MeV) allows a good measurement of the inclusive γ spectrum. Using 3×10^6 $\psi(2S)$ events, they measured $\psi(2S) \to \gamma\chi_{cJ}$ (E1 transitions) and $\psi(2S) \to \gamma\eta_c$ (M1 transition) [11]. Results are shown in Table 1. Note the big change from PDG04 [12] for $\psi(2S) \to \gamma\chi_{c2}$; this will affect χ_{c2} branching fractions! The combined transistions, $\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi, J/\psi \to \mu^+\mu^-, e^+e^-$ have also been measured by BESII [13] and CLEOc [14], and the product branching fractions are shown in Table 2. Branching fractions for $\chi_{CJ} \to \gamma J/\psi$ are given in Table 3. BESII is calculated using the CLEOc branching fractions for $\psi(2S) \to \gamma\chi_{cJ}$ from Table 1 and the BESII results in Table 2.

Table 1
Radiative decay branching fractions.

Decay	PDG04 %	CLEOc % [11]
$\psi(2S) \to \gamma\chi_{c0}$	8.6 ± 0.7	9.22 ± 0.47
$\psi(2S) \to \gamma\chi_{c1}$	8.4 ± 0.8	9.07 ± 0.55
$\psi(2S) \to \gamma\chi_{c2}$	6.4 ± 0.6	9.33 ± 0.63
$\psi(2S) \to \gamma\eta_c$	0.28 ± 0.08	0.32 ± 0.07

3.2. $\psi(2S)$ hadronic transitions

The $\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi, J/\psi \to \mu^+\mu^-, e^+e^-$ decays can also be used to measure the processes $\psi(2S) \to \pi^0 J/\psi$ and $\eta J/\psi$. These and $\psi(2S) \to \pi\pi J/\psi$ results are shown in Table 4 [13–16]. Note that isospin is conserved in the CLEOc $\pi^+\pi^- J/\psi$ to $\pi^0\pi^0 J/\psi$ ratio. Using CLEOc + BESII, we determine

$$R = \frac{\Gamma(\psi(2S) \to \pi^0 J/\psi)}{\Gamma(\psi(2S) \to \eta J/\psi)} = 0.042 \pm 0.004$$

R is much larger than expected using PCAC [17] and may indicate mixing between π^0, η, and η' [18].

Table 2
Product branching fractions: (BESII [13], CLEOc [14])

Decay: $\psi(2S) \to$	PDG04 (%)	BESII (%)	CLEOc (%)
$\gamma\chi_{c0} \to \gamma\gamma J/\psi$	0.101 ± 0.012	–	0.14 ± 0.02
$\gamma\chi_{c1} \to \gamma\gamma J/\psi$	2.67 ± 0.15	2.81 ± 0.24	3.44 ± 0.14
$\gamma\chi_{c2} \to \gamma\gamma J/\psi$	1.30 ± 0.08	1.62 ± 0.13	1.85 ± 0.08

Table 3
$\chi_C J \to \gamma J/\psi$ branching fractions. BESII calculated using the BES results of Table 2 and the CLEOc results of Table 1.

Decay	PDG04 (%)	BESII (%)	CLEOc [14] (%)
χ_{c0}	1.18 ± 0.14	–	2.0 ± 0.3
χ_{c1}	31.6 ± 3.3	31.0 ± 3.2	37.9 ± 2.2
χ_{c2}	20.2 ± 1.7	17.4 ± 1.8	19.9 ± 1.3

4. Hadronic decays of charmonium

Decays of J/ψ, η_C, χ_{CJ}, and $\psi(2S)$ with definite J and I are ideal to study meson and baryon spectroscopy. In particular, radiative decays of J/ψ are ideal for glueball searches [19]. As an example, Fig. 1 shows Dalitz plots, projections, and the result of a partial wave analysis fit for the decay $\chi_{C0} \to \pi^+\pi^- K^+K^-$. The Dalitz plots show rich structure, and these decays are ideal for studying scalar states [20].

The pQCD 12% rule [21,22] states that single J/ψ and $\psi(2S)$ hadronic decays to final state X proceed via the annihilation of the $C\bar{C}$ pair into three gluons or a virtual photon, and the decay

Table 4
Hadronic transitions: $\psi(2S)$ Branching fractions.

Decay	PDG04	BES	CLEOc [14]
$\pi^0 J/\psi$	0.10 ± 0.02 %	$0.14 \pm 0.01 \pm 0.01$ % [13]	$0.13 \pm 0.01 \pm 0.01$ %
$\eta J/\psi$	3.16 ± 0.22 %	$2.98 \pm 0.09 \pm 0.23$ % [13]	$3.25 \pm 0.06 \pm 0.11$ %
$\pi^+\pi^- J/\psi$	31.7 ± 1.1 %	32.3 ± 1.4 % [15]	$33.54 \pm 0.14 \pm 1.10$ %
$\pi^0\pi^0 J/\psi$	18.8 ± 1.2 %	–	$16.52 \pm 0.14 \pm 0.58$ %
$\frac{\pi^+\pi^- J/\psi}{\pi^0\pi^0 J/\psi}$	1.69 ± 0.12	$1.75 \pm 0.03 \pm 0.08$ [16]	2.03 ± 0.04

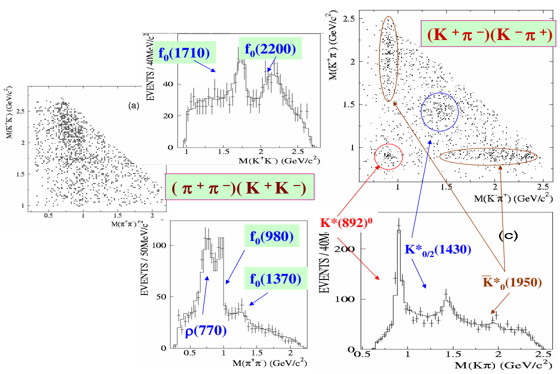

Figure 1. Dalitz plots, projections, and the result of a partial wave analysis fit for the decay $\chi_{C0} \to \pi^+\pi^- K^+K^-$.

rate should be determined by the wave function at the origin squared ($|\psi(0)|^2$), which is measured by the decay rate into leptons, and therefore

$$Q_h = \frac{B(\psi(2S) \to X)}{B(J/\psi \to X)} = \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \sim 12\%$$

MARK-II found that a number of decays obeyed this rule but that it was badly violated for VP decays to $\rho\pi$ and K^*K, the so called $\rho\pi$ puzzle [23]. The suppression was confirmed by BESI with higher sensitivity, and BESI also found the VT mode to be suppressed [24].

There have many attempts at theoretical explanations [25]. Together BESII, CLEOc, and BaBar have all made many new J/ψ and $\psi(2S)$ branching fraction measurements [26]. A summary of a few new Q_h values from BESII is shown in Fig. 2. There is no obvious rule to categorize the suppressed, the enhanced, and the normal decay modes of the J/ψ and $\psi(2S)$. Hopefully the many new measurements will help in understanding this problem.

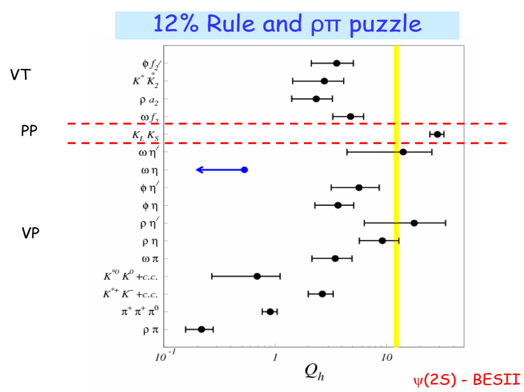

Figure 2. Measurements of Q_h for some two body decays by BESII.

5. $\psi(3770)$

The $\psi(3770)$ is just above $D\bar{D}$ threshold so it decays mostly to correlated $D\bar{D}$ pairs. Its importance for charm physics has been stressed by many speakers. BESII has 34 pb^{-1} at and around the $\psi(3770)$, and CLEOc has 281 pb^{-1} at the $\psi(3770)$. These samples not only allow precision charm decay measurements, they also better our understanding of the $\psi(3770)$.

The $\psi(3770)$ is thought to be a mixture of S and D wave (mostly D), but since the $\psi(3770)$ is above DD-bar threshold it is expected to decay mostly to $D\bar{D}$. BESII found evidence (see Fig. 3) for non $D\bar{D}$ decay in

$\psi(3770) \to \pi^+\pi^- J/\psi$ [27] with a branching fraction $B(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.34 \pm 0.14 \pm 0.09)\%$ and a width of $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = (80 \pm 33 \pm 23)$ keV, to be compared to a prediction of 26 to 147 keV [10]. CLEOc with a larger data sample confirmed this with $B(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.189 \pm 0.020 \pm 0.020)\%$ [28].

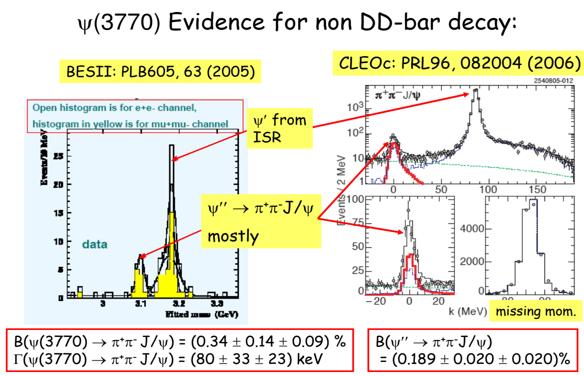

Figure 3. Evidence for non $D\bar{D}$ decay through $\psi(3770) \to \pi^+\pi^- J/\psi$ by BESII and CLEOc.

CLEOc has also found evidence for non $D\bar{D}$ decays in the hadronic transitions, $\psi(3770) \to \pi^0\pi^0 J/\psi$ and $\psi(3770) \to \eta J/\psi$ [28] and in radiative decays $\psi(3770) \to \gamma\chi_{CJ}$ [29,30]. However, they have found that hadronic decays at the $\psi(3770)$ are mostly consistent with continuum production [31].

6. Future

We can expect further progress from B factories, BESII, and CLEOc. However, BaBar and CLEOc will stop running in 2008. BEPCII with a design luminosity of 1×10^{33} cm^{-2} s^{-1} and a brand new BESIII detector will start commissioning in summer of 2007 [32]. With B factories, CLEOc, and BESIII, the future of charm and charmonium physics is very bright.

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